Chapter 4
Urban Infrastructure and Use of Mass Balance Models for Water and Salt

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4.1 Introduction

Urban infrastructure supplies water to urban areas and drains away sewage and stormwater. These services are critical to the health and prosperity of modern cities. The built infrastructure includes reservoirs, concrete channels, canals, pipes, pumps, and treatment facilities. This infrastructure is usually owned by public entities (cities or water and sewer agencies). Some smaller sized systems are operated by private companies who can adequately train personnel and achieve economies of scale through operating facilities for several localized treatment and distribution systems. Privatization for operations of large-sized water and wastewater systems (i.e., serving >100,000 people) is slowly expanding in the USA, although the cities still own the infrastructure. Public entities bill private residences, commercial and industrial users, etc. to repay the enormous capital investment of this infrastructure, reoccurring replacement and repair and continuous operating expenses. In fact, the electrical demand for pumping water is usually among the highest single recurring expenses for cities, just behind the high costs related to human resources (salaries, benefits, etc). Some of these facilities are above ground, but hundreds of miles of pipes are buried 3 to 20 ft underground. Most components of this built urban water environment are constructed with materials designed to last 25 to 50 years and represent enormous capital investments (i.e., billions of dollars). Creation and operation of urban water systems fundamentally changes the natural hydrologic flow across landscapes (Chapter 2). Consequently, studying water and material fluxes in urban settings requires a basic understanding of the key components comprising the urban water infrastructure.

This chapter describes the typical water consumption/production patterns within urban societies and the infrastructure required to support the efficient use and movement of water. The first part of the chapter provides an overview on critical components of the urban water system. The second part of the chapter is a case

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study into modeling fluxes of water and pollutants through an arid-region water infrastructure system. Water in arid regions exemplifies the degree to which urban water systems can become almost completely managed, with very little remnants of natural hydrologic flow or aqueous material fluxes.

4.2 Urban Water Infrastructure Components

Urban water systems include four major categories of engineered infrastructure components: (1) water supply, (2) drinking water, (3) wastewater/sewage, and (4) stormwater. Water supply, drinking water and wastewater systems are interdependent upon each other. Information is presented below for each of the major urban water infrastructure components.

4.2.1 Water Supply

Urban areas require water for agricultural, industry, commercial, and residential uses (Fig. 4.1). Agriculture and several types of large industries (e.g., power production facilities) use large quantities of water which is usually separate from water that is centrally treated at a water treatment plant and pumped into pipe networks for commercial or residential water users. A common unit for measuring volumes of water is *acre-feet*, or the volume of water that when spread out covers 1 acre of land to a depth of 1 foot. (1 acre-ft equals 43,560 $ft^3 \approx 325{,}800$ gallons $\approx 1230\ m^3$). For the last 20 years in the USA, water usage has been approximately 400 billion gallons per day (USGS, 2004). Agricultural crops use approximately 34% of this

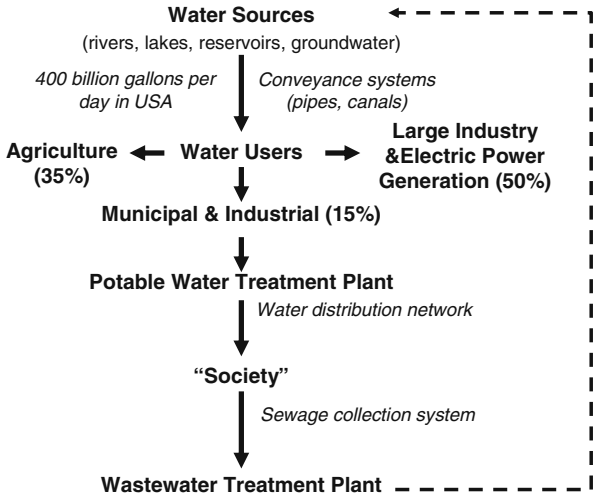

Fig. 4.1 Connectivity of water supply and water usage systems. Details provided for the urban water system. *Lines* indicate flow direction of water. *Dashed line* indicates discharge of treated wastewater effluent back to water sources

water, through application of 6 to >10 ft of water per acre per year. Power generation is the largest water user with the national industrial sector, approximately 50% of the domestic water usage. The most common form of electricity production, thermo-electric power generation from coal, oil, nuclear, consumes approximately 21 gallons per kilo-watt-hour (kWhr) of electricity produced; a typical residential house uses on the order of 20 kWhr of electricity per day, which equates to using over 400 gallons per day per household of water via electricity production. Approximately half of this water comes from fresh water supplies and half from brackish water source unsuitable for human consumption. A portion of the water withdrawn from surface waters for power production evaporates, and is termed *consumptive use*. However, most water passes through the power plant, returns as warm water to the river or lake, and is termed *non-consumptive use*. The returning warmer water can pose risks to downstream aquatic organisms and fisheries.

In addition to industrial water use, a typical "person in society" is responsible for consumption of approximately 90 to 320 gallons per capita per day (*gpcd*) of treated potable water. Potable drinking water is usually centrally treated (water treatment plant, WTP) and pumped out into the urban area under pressure in a vast underground pipe network. Potable water uses include direct drinking and cooking water, toilets, bathing, clothes washing, outdoor irrigation, restaurants, car washes, commercial buildings, malls, and industries. Figure 4.2 illustrates the distribution of annual water use by households across the country. Indoor water use, which is non-consumptive because it returns as sewage to centralized wastewater treatment plants (WWTPs), averages 63,000 gallons per household per year (roughly 69 gpcd) and has very little geographic dependence. However, outdoor water use (consumptive use) varies geographically from <8000 gallons per household per year to >200,000 gallons per household per year.

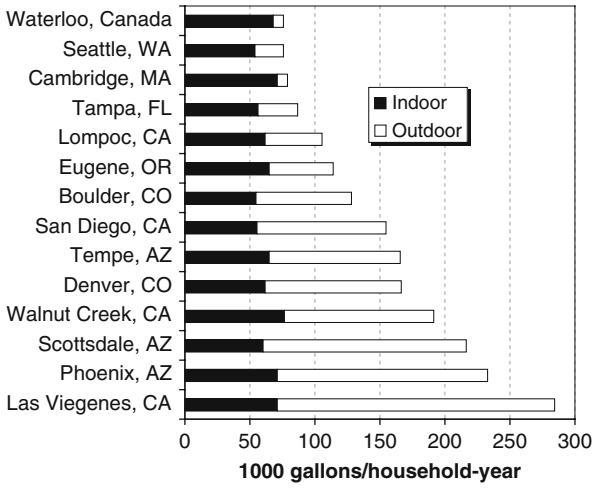

Fig. 4.2 Geographic distribution of indoor and outdoor water use patterns for households served with public drinking water (adapted from Mayer et al. 1999)

Water demands exhibit seasonal patterns. Agriculture needs more water during the summer. Thermo-electric power plants require more cooling water during peak energy use periods (i.e., summer time). Potable water demand is roughly two to three times greater during summer than winter months, and is almost regardless of geographic location.

Rivers, lakes, reservoirs, and groundwater all can store and serve as water supply sources for urban uses. There are roughly 55,000 public water supply systems in the USA. Approximately 64% of public water supplies are surface waters and 36% are groundwaters. Smaller communities (<50,000 residents) are more often served by groundwater. Many urban areas import water from water sources located tens to hundreds of miles away to meet the seasonal and total water demands of the urban population. This is true in both temperate areas (e.g., New York City imports water from the Catskill Mountains over 50 miles away), mountainous areas (Denver, located on the east side of the continental divide, imports water from the wetter western side of the divide) and arid areas (Southern California imports water hundreds of miles from both the Sacramento River in Northern California or Colorado River in Arizona). Surface water impoundments (i.e., lakes and reservoirs) are critical for storing water during wetter periods of the year(s) for drying periods. The average time water spends in a reservoir (i.e., *hydraulic residence times*, HRT) can vary from a few months in Eastern US reservoirs to years (western US reservoirs) or decades (Great Lakes). HRT is calculated by dividing the reservoir volume (ft^3) by the outflow (ft^3 per day, month, or year). Reservoirs are usually located on rivers, where a dam is constructed to allow the reservoir to fill (Fig. 4.3). Outlet structures have "gates" at different depths to permit discharge/release of water from the reservoir downstream into the river.

The water quality of surface waters can be adversely affected by natural or anthropogenic means. During warmer months of the year reservoirs will thermally stratify as warmer, less dense water "floats" above colder, denser water in the depths

Fig. 4.3 Photographs of a typical outlet structure located in a reservoir (Lake Pleasant, Arizona)

of a lake. In the upper sunlight strata of a lake, algae grow and can produce organic chemicals that are neural toxins or cause off-flavor or odors (Baker et al. 2000). Increases in nutrient levels from land surfaces or industrial discharges can lead to increased algae activity, which detrimentally impacts the quality of the water as a drinking water supply and would necessitate more costly water treatment processes to be implemented later. In the lower strata of a lake decomposition of organic matter that settles to the bottom causes bacteria to grow and consume oxygen. When all the dissolved oxygen is consumed, biogeochemical processes can transform metals present in sediments (e.g., arsenic, manganese, iron) into forms that are soluble in the water and would require treatment to remove them prior to use as drinking water. Land development within watersheds lead to numerous adverse water quality effects on rivers and lakes that impact not only recreational and fishing activities (i.e., nutrients or bacteria in stormwater runoff), but also leads to more extensive treatment in drinking water treatment plants before it can be safe to drink.

Groundwater is also an important water supply source for several reasons: (1) groundwater does not require construction of large above ground reservoirs, (2) groundwater can be pumped during periods of drought when reservoirs are low, and (3) groundwater usually is of fairly high quality. Groundwater is "stored" and flows in the pores of the sediment. Wells are drilled into the ground to depths of tens to hundreds of feet to access the water. Most larger municipal groundwater systems require pumping to bring the water to the surface for use, as the aquifers are not "artesian" wells. Artesian wells are in-confined aquifers and water will flow upwards out of the well without need for pumping.

Historically groundwater supplies required little, if any, treatment before potable use. Groundwaters may require treatment to remove naturally occurring pollutants (e.g., arsenic), unpleasant odors (e.g., hydrogen sulfide), high mineral content (hardness or other salts), chemicals that cause staining (e.g., iron or manganese) or anthropogenic pollutants (e.g., gasoline additives such as MTBE or solvents such as TCE). Nitrate is among the most pervasive pollutant found in groundwaters across the USA, primarily due to use of nitrogen fertilizers for agriculture. Nitrate percolates through the soil and into the groundwater. In drinking water nitrate causes methemoglobinemia, or "blue baby" disease. Many groundwater supplies have been abandoned as drinking water supplies because of nitrate and the costly treatment necessary to remove nitrate. New federal regulations enacted in 2006 (USEPA Groundwater Disinfection Rule) also aims to improve the safety of groundwaters used as drinking water supplies by mandating disinfection to kill microorganisms in the water. Because of pollution and new regulations there is an increasing demand to treat groundwater prior to its use as a drinking water.

Pumping groundwater consumes electricity. The amount of electricity required to lift water out of the ground is a function of the desired flowrate (gallons per minute, gpm), height to which the water has to be lifted out of the ground (feet) and efficiency of the pump. Pumping a series of wells from a depth of 100 ft at a rate of 1 million gallons of water per day (1 MGD), enough to supply roughly 6700 people, would consume roughly 145,000 kWhr of electricity per year. At a cost of $0.10 per kWhr, pumping 1 MGD costs roughly $14,500 per year just for pumping the water.

Unrestricted pumping of groundwater can lead to significant declines in groundwater levels (i.e., mining of groundwater) because the rates of withdrawal are greater than the rates of natural recharge. *Safe yield* is a term that refers to the maximum amount of groundwater that can be withdrawn from an aquifer without long-term decline in its water level because the withdrawal rate is equal to or lower than the rate of natural groundwater recharge. As groundwater levels drop (i.e., water level in wells is deeper) a number of problems emerge: (1) less resilience during droughts as wells run dry, (2) increased cost of pumping water from deeper depths, (3) increased risk of land subsidence, or (4) more variable water quality.

Many municipalities in arid regions intentionally recharge surface water or treated wastewater into the ground, using recharge basins (Fig. 4.4), in an effort to increase future groundwater pumping capabilities without exceeding an aquifers safe yield. Many cities (Palm Springs, metro-Phoenix, Tucson, Colorado Springs, Las Vegas, and southern Florida) use surface recharge, or subsurface injection of water (i.e., aquifer storage and recovery) and subsurface aquifers for long-term storage and even treatment of chemicals in the water (i.e., soil aquifer treatment). Another growing trend is referred to as riverbank filtration. Groundwater wells are drilled adjacent to or laterally beneath rivers and water is "sucked" through sediments

Water is conveyed from surface and ground water supplies to locations of water demand (e.g., farms, industry, potable WTPs). River channels serve as a common conveyance system, but many urban areas also employ large-diameter (8 ft to over 12 ft in diameter) buried pipes or aqueducts (e.g., New York City, Boston, Las Vegas) or concrete-lined canals (Phoenix, San Diego, Los Angeles) to move water. Figure 4.5 illustrates an example of a concrete-lined canal in central Arizona. Concrete linings are used to prevent loss of water from the canal (i.e., seepage into the groundwater).

Fig. 4.4 Recharge basin located near a river channel that has high soil permeabilities. A wastewater treatment plant is located in the background, and treated wastewater flows into this recharge basin to supplement regional groundwater supplies

Fig. 4.5 Typical concrete canal in the western USA delivering water from distant reservoirs and rivers to urban regions in the desert

Potable WTPs purify water to make it suitable for human consumption. Typical *unit treatment processes* involve addition of metal salts that aid in removal of inorganic clay-like particles and biological pathogens (bacteria, virus, protozoa) in sedimentation and filtration systems (i.e., pathogen removal via physical processes), followed by application of chemical disinfectants (chlorine or chloramines) for chemical disinfection. Additional processes (e.g., granular activated carbon in deep filters) can be added to the typical processes to improve removal of organic pollutants or compounds that impart off-flavors or odors to water. Figure 4.6 is an aerial photograph of a drinking water treatment plant with several of the unit treatment processes labeled. It takes roughly 4 to 6 hours for water to pass through a WTP.

There are hundreds of miles of buried pipes in urban areas to deliver water from water sources (WTPs, groundwater wells) to houses, commercial buildings, schools, etc. High pressure pumps pressurize the water to roughly 80 pounds per square inch (psi) in buried pipe networks. The pressure of 80 psi is roughly enough pressure to pump water to an elevation of 180 ft above ground level ($\sim$ a 15 story building). Pressure is needed to move water across the topography of a city, provide pressure to flow water out of showers and other domestic uses, and most importantly provide sufficient pressure to fight fires. In fact, the size of pipes buried in the ground

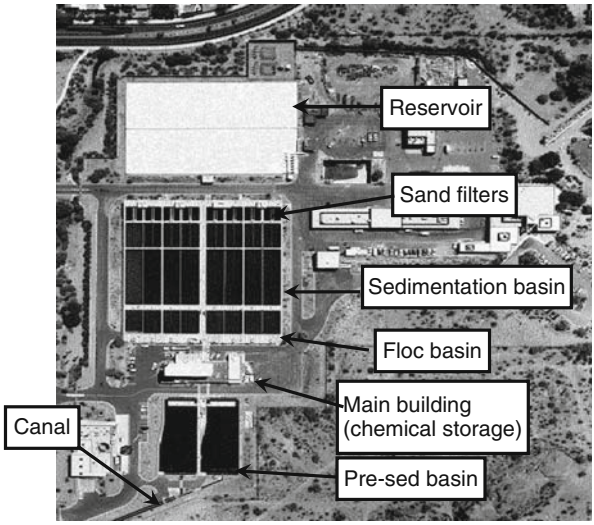

Fig. 4.6 Aerial photograph of a water treatment plant in Arizona. Water flows from the canal, into the presedimentation basin, through the flocculation system where coagulants are added to help remove particles and organics, into the sedimentation basins where particles settle out into sand filters (3 to 8 ft deep) and particle removal also occurs, then chlorine is added before water flows into the reservoir. Drinking water is pumped from the reservoir into the pipe network into "society". Note the facility is surrounded by desert and encroaching urban development from the top of the picture frame

and minimum required pressures in water distribution system networks of pipes is designed around the ability to meet required fire flow and fire fighting pressure requirements. Pipes range from 8 ft in diameter leaving WTPs, with many common pipes being 24 to 48 inches in diameter, and pipes in residential neighborhoods on the order of 2 to 6 inches in diameter. Most pipes are constructed from some type of steel, except for the larger pipes which are lined concrete pipes. There are hundreds to thousands of miles of buried pipes buried in the ground and used to move around treated water, and thousands of valves to control the flow (i.e., water distribution system). Water moves through these buried pipes at approximately 1 foot per minute, resulting in frictional losses which decrease the pressure of water in the pipes. Because of these pressure drops and changes in elevation, most cities have multiple "pressure zones" where water pumped again to increase pressure to serve the public. Storage tanks scattered around cities help regulate pressures and available water, such as the large metal tanks typically located atop mountains or "lollipop" metal tanks elevated into the air. Average travel times of water from a centralized WTP to your house may range from 1 to 3 days, and in some areas take over 7 days.

Water distributions systems plan an important role in understanding the overall sustainability of urban water systems. First, water is heavy and pumps required to move the water consume significant amounts of electricity. Approximately 30% to

50% of the entire electrical use for all city services comes from pumping of water. Second, there are nearly 240,000 water main breaks per year in the USA. These breaks and slow leaks lead to a loss of nearly 1.7 trillion gallons per year (USEPA 2007).

4.2.2 Sewage Collection and Treatment

Depending upon the region of the country, between 50% and 75% of the water distributed from the WTP (~ 100 gpcd) is discharged to sanitary sewers. The remainder is used for outdoor irrigation or evaporated in commercial cooling systems (i.e., consumptive uses). Domestic water used for showers, toilets, and washing clothes mixes with sewage from restaurants and industry in a network of buried pipes (sewage collection systems). In contrast to the potable water system which contains pressurized water in pipes (i.e., pipes are full of water), sewage collection systems flow by gravity in partially full-flowing pipes. As such the pipe diameters are larger. Common materials are clay or lined concrete. Manholes are located every 300 to 500 ft for *every* pipe within sewage collection systems in order to provide (1) locations to re-align (i.e., turn) pipes (2) access for maintenance, and (3) ventilation of volatile gases (odors, methane, etc).

Sewage flows from households and commercial sources through the sewage collection system to centralized WWTPs. WWTPs include sedimentation systems to remove sand, grit and other heavy debris, but rely primarily on biological treatment processes to purify the water (Fig. 4.7). Bacteria consume nutrients (carbon and nitrogen) in the sewage (i.e., proteins, carbohydrates, soaps, etc) and convert them into gases (methane, carbon dioxide, nitrous oxides) and biomass (bacterial cells) (see Chapter 5). The gases are discharged to the atmosphere, although methane can be captured and burned to heat water and keep the bacteria warm. All the gases pose

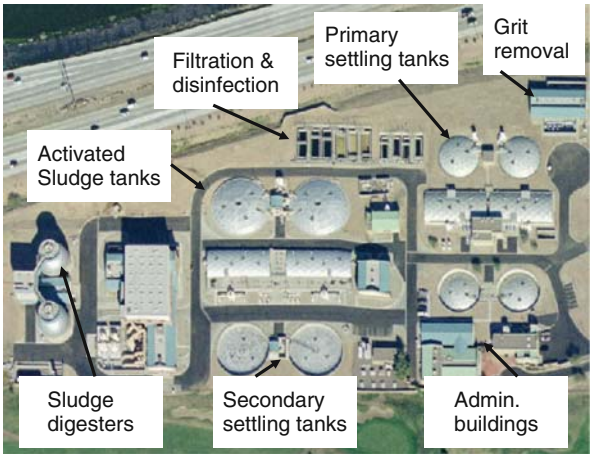

Fig. 4.7 Aerial photo of a wastewater treatment plant. Sewage flows into the grit removal to remove large objects, then into primary settling tanks, activated sludge tanks, secondary settling tanks, filtration and disinfection systems. Settled materials (biosolids) are digested in sludge digesters where they produce methane gas that is recovered to help operate the facility

somewhat of a global warming concern. Biomass is dewatered (i.e., squeezed through filter presses) and then (1) sold as fertilizer, (2) incinerated to produce electricity, or (3) landfilled. To reduce the volume of biomass solids that have to be trucked off and disposed, larger WWTPs operate anaerobic digesters to produce methane, which is collected and burned to provide electricity and/or heating at the facility.

Treated wastewater is briefly disinfected using chlorine or ultraviolet light before being discharged into surface waters (rivers, lakes, streams) or groundwater (i.e., Fig. 4.3). The quality of wastewater effluent is often characterized by (1) the organic carbon strength (i.e., biochemical oxygen demand – see Chapter 5), because bacteria growing in receiving waters consume this carbon and simultaneously consume dissolved oxygen (DO) in water, leading to fish kills, (2) the amount of nitrogen and/or phosphorous because algae growth from these nutrients lead to biomass in rivers which consumes oxygen as it decays, (3) levels of bacteria that may inhibit recreational use of the rivers, and (4) known toxic, regulated pollutants (heavy metals, pesticides, etc).

In addition to known toxins, there has been growing concern for the presence of trace-level (parts per trillion) of pharmaceutical compounds (e.g., synthetic estrogen from birth control) in sewage effluents which can affect the gender of fish in rivers. Therefore, where these or other issues are a concern advanced wastewater treatment processes are added to the WWTP. There is also growing concern about salt pollution for the southwestern USA, because household detergents and chemicals, food, water softeners and industries add salt to sewage. Salt pickup is usually 200 to 400 mg/L, which can make it difficult to reuse treated wastewater for beneficial uses (public outdoor irrigation) if the potable water also has a high level of salts. Salt concentrations, measured as total dissolved solids (TDS), exceeding 1000 to 1200 mg/L will not be suitable for irrigation of most grasses (i.e., golf courses, parks, etc). WWTPs that need to remove salts and trace organics often use *reverse osmosis* (RO) technologies. Because a lot of energy is needed to pressure water for RO systems (e.g., operating pressures are 200 to 300 psi), they are very energy intensive. Inclusion of RO treatment at WWTPs more than doubles the initial infrastructure and operating costs. Figure 4.8 illustrates a mass balance on water and salt during RO treatment. Treating 10 MGD of wastewater containing 1130 mg/L of total dissolved solids (i.e., salts) by RO will produce approximately 8.5 MGD of low-salt (27 mg/L), clean, permeate water and 1.5 MGD of high-salt (7380 mg/L) reject water. Disposal of the reject water can be challenging, as it poses risks to aquatic life because of the high salt levels.

4.2.3 Stormwater Collection

Removing rainwater from streets and land surfaces is critical to prevent localized flooding and associated damages. Therefore, urban water systems include a third network system comprised of stormwater drains, localized treatment, and buried pipe collection systems. Localized treatment usually involve grass lined swales or

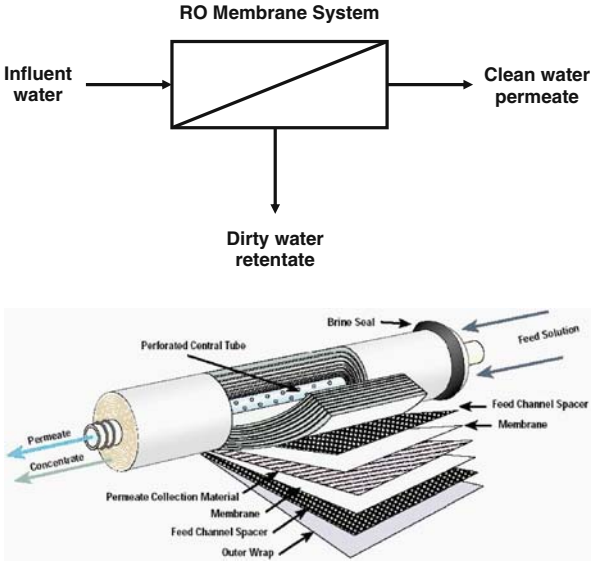

Fig. 4.8 Representation of a mass balance on water and salt in a reverse osmosis (RO) system and image of RO membranes at a wastewater treatment plant. Membrane systems include high pressure pumps, chemical feed facilities and membrane elements. Bottom photograph is spiral-wound RO membrane element (source: www.pyrocrystal.it/sito%20secondario2/osmosys.htm)

small retention basins located in neighborhoods, parking lots, and commercial sites. Roughly 50% of many pollutants in stormwater (e.g., metals, nutrients, organic toxins, bacteria) are associated with particulate matter. Providing time for particles to settle our or filter out dramatically improves the quality of stormwater. However, 50% of the pollutants are not associated with particles (i.e., soluble) and remain in the water. Some pollutants, such as ions from road salts are 100% soluble and are not removed by filtration processes. Common stormwater control measures include grass buffer strips, grass-lined swales, retention ponds, or infiltration basins (See Chapter 5).

Rainfall patterns vary widely across the USA, and as such stormwater systems are designed around local hydrologic considerations. Rainfall frequency and intensity historic data is used to design the number and size of stormwater drains and pipe systems. Roads are beveled/sloped to prevent flooding, but must be drained. Drains are usually located every 500 ft along roads, and more frequent around intersections. Stormwater pipes are large diameter (12 to over 96 inches in diameter) and located beneath nearly every street. Stormwater often flows without any type of treatment to improve water quality into rivers or lakes. In older communities such as Pittsburg, New York and Chicago, stormwater and sewage systems remain connected; these sewers are termed *combined sewers*. This is undesirable, because during larger flow events not all this water can be treated, and consequently is discharged to rivers and streams without treatment (i.e., *combined sewer overflow*). The surface waters become polluted with untreated sewage, nutrients, and microorganisms. There are up to 75,000 sanitary sewer overflow events per year in the USA, resulting in discharge of 3 to 10 billion gallons of untreated wastewater (USEPA 2007). This leads

to up to 3700 illnesses annually due to exposure in recreational waters contaminated by sanitary sewer overflows (USEPA 2007).

4.3 Case Study of Modern Integrated Urban water Modeling

The text above describes the components of modern urban water systems. However, integration of these systems across the urban landscape leads to profound differences in urban hydraulics from natural hydrologic processes. A case study is described here to provide an example of how several urban water components become interconnected. The example is from a city in the Sonoran Desert of Arizona because less water falls within city boundaries than is required by the >250,000 residences. Therefore, it serves as a representative model for many other cities around the country that face similar water issues. In addition to "wet" water alone, the quality of the water is modeled because this can affect the beneficial uses of the water.

4.3.1 Modeling Approach

A modeling approach that integrates water sources/uses, water treatment and distribution, wastewater collection and treatment and stormwater will be discussed in terms of both the quantity and quality of water for one city in the southwestern USA (Scottsdale, Arizona). Per capita water use is over 150 gpcd and there are more than 20 golf courses that exclusively use reclaimed wastewater for irrigation. Salt levels are naturally high in the southwestern USA, and as an inland basin (no connection to the ocean) salt accumulation in soils and economic impact on in-home and commercial plumbing appliances are serious concerns. Salts preclude many beneficial uses of water. When water evaporates during outdoor irrigation, the salt in the water stays behind and accumulates in the soil and/or groundwater. This poses important risks to long-term sustainability of soils for growing plants since salts in the root zone inhibit or prevent plant growth, and salts in groundwater leads to undrinkable water unless RO technologies are employed to desalt the water. Because salts move through the urban infrastructure without evaporating, they are good tracers of other pollutants in the water. For these reasons, salts are used in this case study model as an indicator of water quality.

A single city is modeled for one year, but the concepts and models developed herein are transferrable to other cities, over any timescale, and can be run under any desirable scenario (e.g., long-term droughts, floods, urban development growth patterns, etc). These activities are currently underway and are providing deep insight as long-term management planning techniques.

The City of Scottsdale, Arizona was modeled. It has a population of nearly 250,000, spans 180 square miles, and annually receives 9 inches of precipitation. Potable water supplies for Scottsdale include Salt River and Verde River water delivered through Salt River Project (SRP), Colorado River water delivered through

Central Arizona Project (CAP) canal, and ground water wells. There are between 20 and 25 golf courses in the city. Wastewater is treated and reclaimed for golf course irrigation as well as groundwater recharge. Most stormwater runoff is conveyed in the Indian Bend Wash (IBW) south to the Salt River. A few other stormwater drainages exist but constitute minimal flow and most water in these washes and other areas of the cities percolate into the ground. Data on drinking water and wastewater was supplied by the city and other agencies.

A conceptual illustration for the modeling framework is presented in Fig. 4.9. The model illustrates inflow and outflow of water, which carries dissolved salts, through the city boundaries. Within the city water is used. The conceptual model

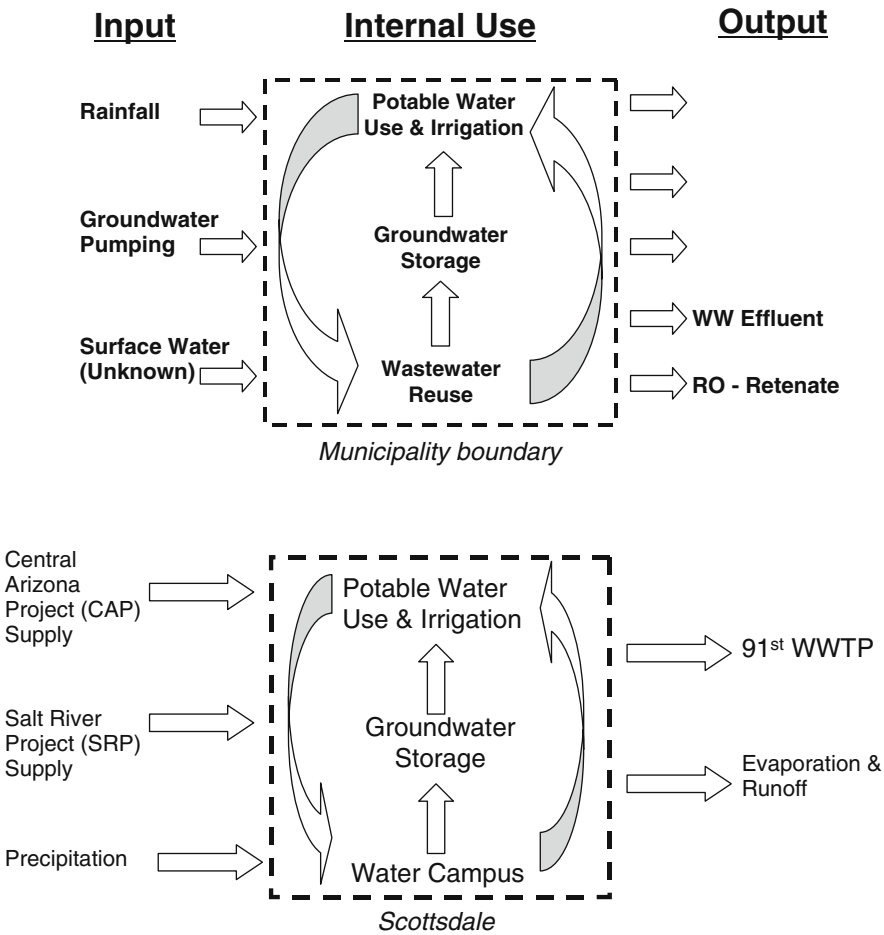

Fig. 4.9 Conceptual framework for integrated urban water modeling of water and salt mass balances. *Upper diagram* is general for an urban area. *Lower diagram* is specific for Scottsdale, Arizona

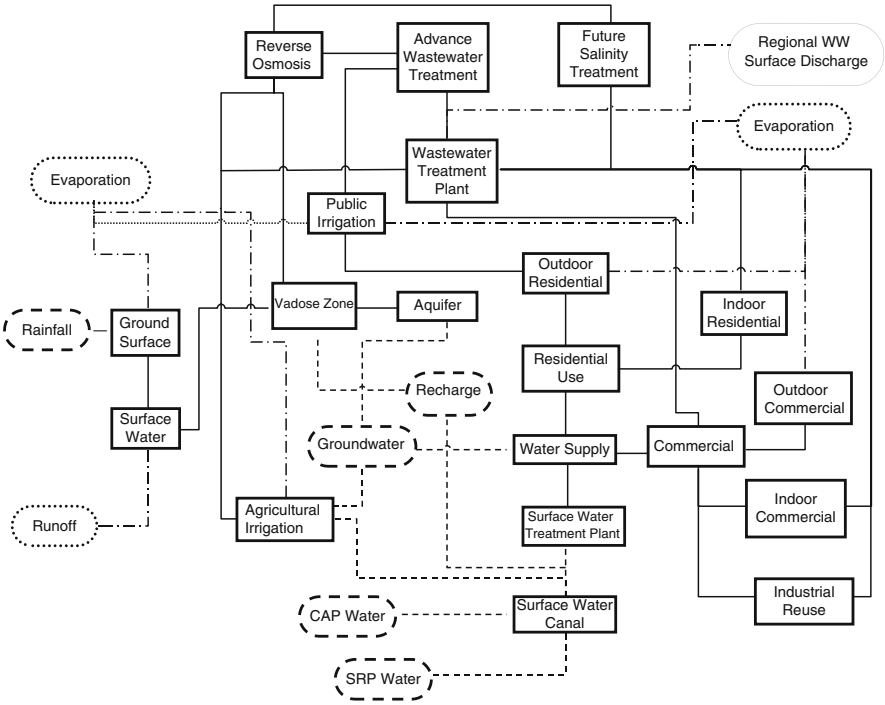

Fig. 4.10 Schematic representation of water and salt flux model. *Ovals* and *dashed lines* represent sources of water into the city or processes that result in water leaving the city. *Rectangles* and *solid lines* represent parts of the urban water system that use water

was mathematically represented using a simulation software program (Powersim Software (www.powersim.com)). PowerSim simulates multi-source fluxes (i.e., movement of materials across time). The PowerSim representation of water quantity fluxes for the City of Scottsdale is illustrated in Fig. 4.10. Water sources (ovals with dashed lines) or sinks (ovals with dotted lines) are linked (arrows) to storage components (rectangles). The storage components include WTPs and WWTPs, and other key aspects for the urban system. The vadose zone (unsaturated soils between the ground surface and groundwater table) and groundwater are represented as separate components because of long retention times in each and because accumulation of water (or salt) in these components have significantly different management implications. "Society" is represented as a single component (labeled "Potable Use") because it fundamentally changes where water is used (i.e., indoor/outdoor use, changes water quality). Overall the mass balance on water moving into or out of a city, and change in groundwater storage is represented by the following relationship: Input Volume = Outflow Volume + Evaporation Volume + Change in Groundwater Storage Volume (See also Chapter 3). The units of water volume are expressed here as acre-ft. One acre-foot is approximately the amount of water that a typical household uses in one year.

The time dependency of water and salt movement (i.e., flux) for different seasons is captured in the model. In most cases these time-dependent relationships are available from the city (e.g., daily water produced each day of the year), streamflow gauging stations (e.g., ft^3/sec), or estimated using standard empirical relationships (e.g., fraction of rainfall converted to runoff). Details of these relationships are provided elsewhere, and all models are run for the calendar year 2005 (Zhang 2007). As one example, based upon a 30-year continuous rainfall data and runoff capture curve for Phoenix metropolitan area it was found that if a rainfall event was less than 2.5 mm, no runoff is predicted; above 2.5 mm of rainfall (P) the volume of runoff (R) can be estimated ($R = 0.9P - 2.5$) (Guo and Urbonas 2002). Resulting runoff is captured in washes and/or retention basins where the runoff infiltrates into the ground. Only large or longer storm events produce significant runoff (i.e., water not recharged into groundwater).

4.3.2 Water Quantity Mass Balance Modeling

Fluxes of water and salt into/out of one Arizona City over the course of one year is shown in Fig. 4.11. The largest single source of water into the city is actually precipitation, despite being an arid region that receives only 9 inches of rainfall annually. Most of this rainfall occurred over only three or four rainfall events, resulting in "steps" or "pulses" of water into the urban system. Forty nine percent of the rainfall results in percolation into the vadose zone, 40% evaporate, and only 11% leaves as runoff. Potable water use (indoor and outdoor) is second largest water use in the city. The model accounts for seasonal variation in water demand (higher demand in summer than winter months). During the summer nearly all the wastewater is used for outdoor golf course and public parks irrigation, whereas during the winter less irrigation water is needed and it is treated by RO and recharged into the groundwater.

Figure 4.11a shows Scottsdale's annual water balance. The largest single loss of water is evaporation which occurs in response to rainfall and outdoor irrigation practices. Despite common perception, the Sonoran Desert is green because of the ecological function that the rain stimulates. Plants rapidly take up the water and then slowly evaporate the water through photosynthetic processes as the plant grows (i.e., evapotranspiration). In personal yards and public greenways, water is also evapotransipired to keep the community green with living plants. Very little stormwater runoff actually leaves the city boundaries, and only does so at periods related to the intermittent rainfall events. Only 20% of the water imported into Scottsdale from the CAP or SRP canals or fallen as precipitation results in flows out of the city as unused wastewater or stormwater runoff; all other water is internally recycled and 80% of the imported water volume eventually evaporates.

Figure 4.11 also illustrates the importance of subsurface waters for this community. The city pumped 29,000 acre-feet of water per year but only directly recharged 5,800 acre-feet directly back into the aquifer. Another 53,000 acre-feet of water did

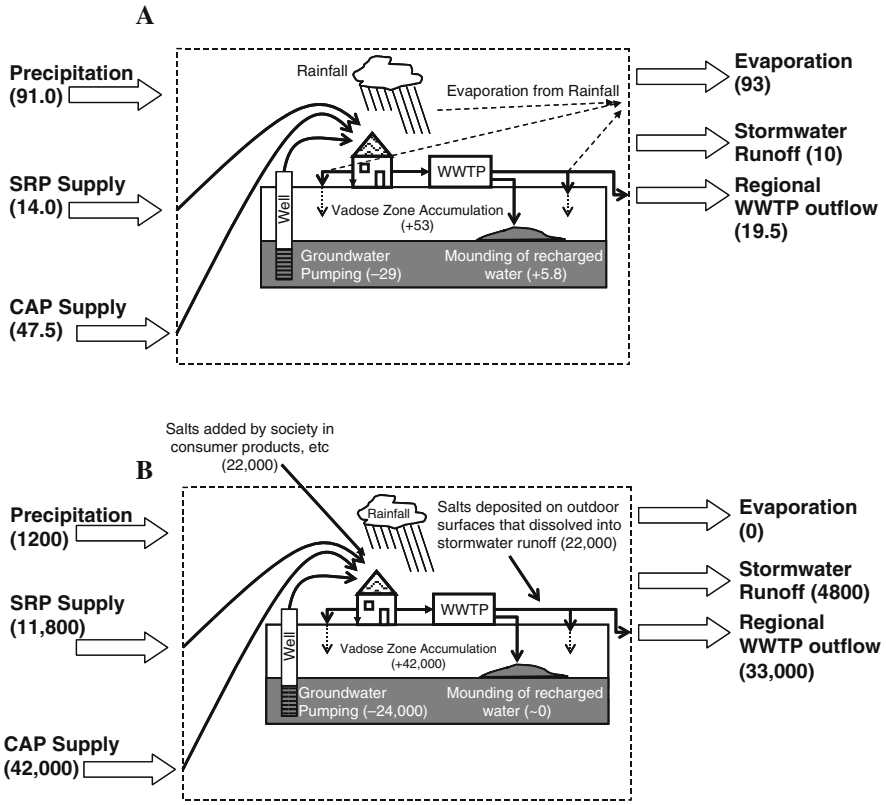

Fig. 4.11 Mass balances of (**a**) water with values in parantheses being the water flux in thousands of acre-feet of water per year (*upper*) and (**b**) salt with values in parentheses being the salt flux in tons of salt per year (*lower*)

not immediately evaporate upon use for irrigation, and is "trapped" in the vadose zone. Downward movement of water through the vadose zone into the groundwater occurs over a time scale of decades. Simultaneously with this downward water migration, gas exchange from the atmosphere and vadose zone will result in slow loss of water vapor from the vadose zone. The current state of knowledge is lacking to predict how much water or how long it will take for water in the vadose to reach the groundwater. This is a major obstacle in predicting the long term sustainability of this community as a significant volume of water is trapped within the vadose zone.

4.3.3 Water Quality Modeling: Salt Mass Balance

Salts occur naturally in many rivers. The geological formations in the southwestern USA consist of sandstones and salt deposits laid down by ancient oceans. As

Table 4.1 Salinity of water within Scottsdale

Component	Selected TDS (mg/L)	TDS Range (mg/L)
CAP Water Supply	650	500–800
SRP Water Supply	620	450–1200
Groundwater Supply	620	200–1500
Wastewater (including reclaimed wastewater for irrigation)	1130	900–1500
Reclaimed water for recharge	27	20–50
Brackish Water from Reverse osmosis treatment of wastewater from AWT	7380	6000–1000
Runoff to the Salt River	350	60–700

surface and ground waters flow through these deposits, salts dissolve into the water. Salt pose potential economic, aesthetic and potential health issues when present at concentrations above 500 mg/L in drinking waters. To address salt flux issue TDS, which is a measurement of the salt concentration of water, was employed in the model as an indicator of water salinity. TDS levels for different water sources were based from local sources (Table 4.1). Salt fluxes (mass per time) are computed from the TDS concentration (mass per volume) times the water flowrate (volume per time) within the PowerSim modeling program. The following equation represents how the balance between salts moving into and out of a city, and the potential to accumulate salts within the city:

$$\begin{aligned}&\text{Inflow Mass of Salt in Water} + \text{Salt Added by Society}\\&\quad = \text{Outflow Mass of Salt in Water} + \text{Salt Accumulated in Soils}\end{aligned}$$

Figure 4.11b summarizes the modeling of salt flux through the city for one year. Over the course of a year the single largest source of salt is from the CAP canal. Groundwater pumping moves 24,000 tons per year of salts out of the ground and into the urban water system. Because of household chemical, water softeners and other uses by the public, a significant amount of salts (22,000 tons per year) are added to sewage water. While rain has very low TDS (<10 mg/L) once it contacts the land surface it "dissolves" (i.e., solubilizes) salts from road and land surfaces that were deposited from the atmosphere, fertilizers, etc. This accounts for approximately another 22,000 tons of salt per year entering the urban water system. Consequently, runoff events result in significant mobilization of salts internally within cities boundaries, and in the runoff leaving the city. Because most of the stormwater flow does not leave city boundaries (Fig. 4.11a), stormwater leaving the city only transport 5% of the salt load out of the city.

While evaporation was the major way water exits the urban system, evaporated water is near "distilled" water quality (i.e., carries no salts away). While a small volume of water (15%) leaves the city boundaries as wastewater to a regional treatment facility (91st avenue), this flow accounts for 33,000 tons/year of salt (37% of the salt entering the city) because much of the flow contains RO brine concentrates from the city advanced wastewater treatment facility. The remaining salt, nearly 42,000 tons per year, enters the vadose zone as irrigation water percolates into the soil. As irrigation water is evapotranspired, the salts stay behind. Of the salts entering the vadose zone, 45% is from residential landscape water, 30% from percolation of stormwater runoff, 23% from golf-course irrigation water, 2% from direct groundwater recharge of CAP water and $<1\%$ from injection of RO permeate from reclaimed wastewater. Thus the vadose zone is accumulating significant amounts of salts.

Salts in the vadose zone pose other sustainability issues. Salts accumulated in soils make it difficult to grow grass, trees or shrubs because salts in the root zone are toxic to most plants. Therefore, more irrigation water is needed to move salts deeper than the root zones, which increases water use rates. Long-term accumulation of salts in the soil will also decrease permeability of the soils, preventing the vertical movement of water. Salt accumulation in groundwater will require more costly treatment of the water (e.g., RO) in order to use the water for drinking or other purposes. The migration rate of salts through the vadose zone may be on the order of 10 to 20 ft/year in agricultural soils that are heavily irrigated, but is probably significantly slower under residential irrigation practices and is currently unknown. Future research needs to determine rates of vertical water and salt movement in residential settings.

4.3.4 Using Integrated Water Models for Urban Cities

The case study demonstrates for a single city with unique water quantity and quality (salts) issues. Central to the model is the linkage between the many different components of the urban water system (stormwater, imported surface water, groundwater, wastewater), which are present in every city. In other work this modeling platform has been used to investigate several interconnected cities or larger urban regions. The model allows planners and engineers to consider a future with new or different infrastructure, which can easily be represented as "ovals" and "flux lines" in Fig. 4.10. It is quite easy to change the water quality parameter of concern, from salts to nitrate for example.

One year was simulated in the case study, but the model has also been run for 30 consecutive years into the future. The ability to simulate future scenarios is critical to identify non-sustainable trends in the urban water system, and potentially how to prevent them from occurring by addressing the issues now. For example in the model there is a large amount of salt accumulating in the vadose zone. The long term effects of these are unknown. On a timescale of 5 to 15 years this may impact plant growth; over several decades the salts may migrate to groundwater;

over longer time periods impereable clay barriers may form that affect soil properties. Being able to simulate the amount of salt entering the vadose zone can now be used to predict these potential issues. Likewise policies to reduce the amount of salt added by society through regulation (e.g., banning water softeners) or through management practices (e.g., street sweeping to remove soluble salts before rainfall events) can be simulated to determine their cost effectiveness in actually reducing salt loads to the vadose zone.

The model shows that most of the water entering Scottsdale is evaporated. Initially this may seem unsustainable. However, most of that evaporated water is serving an ecological function. Irrigation of parks, golf courses, and personal residences supports plants and trees, which in turn support birds and other animals and improve the human quality of life. Due to evaporative cooling, trans-evaporation by plants and direct evaporation of water also counteracts localized urban heat island effects. Developing water policies that limit such irrigation would change this human relationship with water and the environment it supports.

Modeling allows investigation of not only sustainability issues, but also the resilience of cities to various stressors. What would happen if a surface water supply was lost due to terrorism, natural disaster, contamination or other events? The model could easily provide a tool for evaluating various alternatives, which may be complex and involve multiple alternative sources for varying amounts of time. For example, is there enough groundwater pumping capacity to meet water demands during the summer if the SRP water supply is lost?

Modeling allows urban water managers to look towards the future and identify critical knowledge gaps. In the case study, a large volume of water and mass of salt resides within the vadose zone. There is very little knowledge on the rate of movement of water and salt through vadose zones in urban settings. For agricultural areas where 6 to 10 ft of water is applied per year for crops, the rate of downward migration of water and salt is on the order of several feet per year. Residential yards apply far less water and the downward rate of migration is unknown. Maybe none of the water from residential irrigation ever reaches the groundwater. Another example would be to understand the implications of water demand restrictions on generation of wastewater. Initially, it may seem prudent to encourage water conservation to reduce demand of surface waters (e.g., SRP or CAP supplies). If this is achieved at a household level by reducing outdoor irrigation (Fig. 4.2) then the urban ecosystem and its associated benefits will be reduced. If the water demand is achieved through reduced indoor water use, then less wastewater will be generated. In water stressed communities wastewater is a resource that is sold for public or agricultural irrigation uses (i.e., lower water quality standards than required for drinking water). Thus a water conservation policy would reduce the amount of water available as treated wastewater for irrigation, reducing the ecosystem benefits that could be realized or encouraging the use of higher quality water sources (e.g., groundwater) to irrigate those areas. Either way, implementing water conservation policies would alter the flow of water throughout the urban water system, potentially reduce ecosystem services, and requires an integrated model to understand the secondary and tertiary effects of such management planning.

4.4 Summary

This chapter introduced the major water infrastructure components and demonstrated through a case study that they are intimately connected and affect the movement of water and dissolved chemicals in water. In the past, engineers have modeled each system separately (water supply reservoirs or groundwater, WTP, WWTP, stormwater). The future of urban water systems modeling involves linking these models together across time (days, weeks, months, years, decades) and space (towns, cities, regional centers). The case study illustrated here used historic data. In order to make the models predictive in nature, mathematical algorithms should be incorporated into the models to represent water demand and use, etc. By doing so, long term effects of population growth, water use pattern changes due to pricing of water or economics of water pricing, droughts or floods due to climate change, etc can be simulated.

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References

Baker, L., P. Westerhoff, M. Sommerfeld, D. Bruce, D. Dempster, Q. Hu, and D. Lowry. 2000. Multiple barrier approach for controlling taste and odor in Phoenix′s water supply system, pp. 1–11. In: AWWA WQTC Conference, Salt Lake City, UT.

Guo, J. C. Y., and B. Urbonas. 2002. Runoff capture and delivery curves for storm-water quality control designs. Journal of Water Resources Planning and Management **128**:208–215.

Mayer, P. W., W. B. DeOreo, E. M. Opitz, J. C. Klefer, W. Y. Davis, and J. O. Nelson. 1999. Residential End Uses of Water. Awwa Research Foundation, Denver CO.

USEPA. 2007. Aging Water Infrastructure: Addressing the Challenge Through Innovation.

Zhang, P. 2007. Urban Water Supply, Salt Flux and Water Use. Masters of Science Thesis. Arizona State University, Tempe, AZ.